A novel missense mutation of *SLC7A9* frequent in Japanese cystinuria cases affecting the C-terminus of the transporter

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Cystinuria is caused by the inherited defect of apical membrane transport systems for cystine and dibasic amino acids in renal proximal tubules. Mutations in either *SLC7A9* or *SLC3A1* gene result in cystinuria. The mutations of *SLC7A9* gene have been identified mainly from Italian, Libyan Jewish, North American, and Spanish patients. In the present study, we have analyzed cystinuria cases from oriental population (mostly Japanese). Mutation analyses of *SLC7A9* and *SLC3A1* genes were performed on 41 cystinuria patients. The uptake of ^{14}C-labeled cystine in COS-7 cells was measured to determine the functional properties of mutants. The protein expression and localization were examined by Western blot and confocal laser-scanning microscopy. Among 41 patients analyzed, 35 were found to possess mutations in *SLC7A9*. The most frequent one was a novel missense mutation P482L that affects a residue near the C-terminus end of the protein and causes severe loss of function. In MDCK II and HEK293 cells, we found that P482L protein was expressed and sorted to the plasma membrane as well as wild type. The alteration of Pro^{482} with amino acids with bulky side chains reduced the transport function of $b^{0,+}$AT/BAT1. Interestingly, the mutations of *SLC7A9* for Japanese cystinuria patients are different from those reported for European and American population. The results of the present study contribute toward understanding the distribution and frequency of cystinuria-related mutations of *SLC7A9*.

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Cystinuria (MIM 220100) is an inherited disorder owing to the defective transport of cystine and dibasic amino acids across the epithelial cells of renal proximal tubule and small intestine.[1] The incidence of cystine crystalluria reported in Western countries and in Japan varied from 15 000:1 to 50 000:1.[2,3] The patients suffer from recurrent nephrolithiasis leading to severe renal dysfunctions for which repeated therapies are imperative.[4] Classical cystinuria has been classified into three types (I, II, and III) based on the excretion of cystine and dibasic amino acids in obligate heterozygotes.[5] Type I heterozygotes show a normal amino-acid urinary pattern, whereas type II and III heterozygotes exhibit high or moderate levels of hyperexcretion of cystine and dibasic amino acids.[5] The discovery of a single-membrane-spanning type II membrane glycoprotein rBAT encoded by *SLC3A1*[6–10] and 12-membrane-spanning protein $b^{0,+}$AT/BAT1 encoded by *SLC7A9*[11–13] has brought a breakthrough in the understanding of the molecular basis of cystinuria and cystine transport in the renal proximal tubules.

The analyses of cystinuria patients have revealed distinct cystinuria-related mutations in *SLC3A1* and *SLC7A9* genes.[14,15] It was originally supposed that mutations of *SLC3A1* and *SLC7A9* genes are responsible for type I and non-type I (type II and III) cystinuria, respectively. However, recent developments in the genetics and physiology of cystinuria have not supported such a traditional classification.[16–18] Although *SLC3A1* is associated with the type I urinary phenotype, *SLC7A9* mutations were found in all three subtypes.[16,17] Therefore, a new cystinuria classification based on molecular analysis and not on urinary amino-acid excretion patterns has been proposed: type A, due to two mutations of *SLC3A1*; type B, due to two mutations of *SLC7A9*; and type AB, with one mutation on each of the above-mentioned genes.[17] For *SLC7A9* gene, International Cystinuria Consortium and Rozen and colleagues identified cystinuria-related mutations mainly from Italian, Libyan Jewish, North American, and Spanish patients

and established the genotype–phenotype relation for *SLC7A9*.[12,16–18] In the present study, we have analyzed cystinuria cases from oriental population (mostly Japanese) and found that the mutations of *SLC7A9* for Japanese cystinuria patients are quite different from those reported for European, North American, and Libyan Jewish. We report here that the most frequent one is a novel missense mutation affecting the C-terminus of the transporter protein (Tables 1 and 2).

RESULTS

Mutations of *SLC7A9* and *SLC3A1* found in cystinuria patients

We studied 41 cystinuria patients from 39 cystinuria families potentially representing 78 independent cystinuria-related alleles. They were subjected to the mutation analysis of *SLC7A9* gene by direct sequencing. The mutations of *SLC7A9* gene found in the cystinuria patients are listed in Table 3. They include one frameshift (1105delA) and one nonsense mutation (W69stop) that produce early stop codons, and seven changes affecting single amino-acid residues (V142A, G195R, L223M, N227D, R333W, R333Q, and P482L). Among them, V142A, L223M, N227D, R333Q, 1105delA, and P482L were novel mutations found for the first time in the present investigation, whereas three mutations (W69stop, G195R, and R333W) were reported previously for the European, North American, and Libyan Jewish population.[12,16,18] The amino-acid alterations except V142A and L223M were not found in 50 normal subjects. V142A and L223M were, in contrast, found in normal subjects without cystinuria phenotype. V142A and L223M were found in 23 and 19 alleles out of 50 normal subjects (100 independent alleles), respectively, suggesting that these amino-acid alterations represent polymorphic variations of *SLC7A9*.

The location of the *SLC7A9* mutations is shown at the corresponding amino-acid residues in the 12-transmembrane (TM)-domain model of $b^{0,+}$AT/BAT1 protein in Figure 1. Five cystinuria-specific missense mutations were localized within the putative TM domains 5 and 6 (G195R and N227D), in the putative intracellular loop between TM8 and TM9 (R333W and R333Q), or in the C-terminus (P482L). The one single nucleotide deletion is localized to the portion corresponding to the putative intracellular loops between TM8 and TM9 (1105delA). Three mutations (G195R, R333W, and R333Q) alter amino-acid residues that are conserved for all the human members of the heterodimeric amino-acid transporter family (Figure 1).

Among 41 cystinuria patients examined in the present study, we found mutations of *SLC3A1* in five cases. Two cases without any alterations in *SLC7A9* gene possessed mutations for *SLC3A1*: one as a homozygote for the deletion of T at nucleotide 1820; the other as a compound heterozygote for V183A (T548C)/C673R (T2017C); nucleotide numbers refer to GenBank accession no. NM_000341 for rBAT cDNA.[19] Among four cases with only polymorphic changes (V142A and/or L223M) in *SLC7A9*, two cases possessed mutations for *SLC3A1*: one as a homozygote for the insertion of TA at nucleotide 1898; the other as a compound heterozygote for V183A (T548C)/L346P (T1037C). The other two cases with only polymorphic changes in *SLC7A9* did not possess *SLC3A1* mutations. *SLC3A1* mutations were not found in the cases with cystinuria-specific mutations of *SLC7A9* except one P482L homozygote that also possesses I445T (T1334C) mutation in *SLC3A1*.

Functional analysis of *SLC7A9* mutations

All the *SLC7A9* mutations found in the present study were examined for amino-acid transport activity. As shown in Figure 2, the cystinuria-specific mutations such as W69stop, G195R, N227D, R333Q, R333W, 1105delA, and P482L exhibited remarkable decrease in cystine transport activity compared with wild-type $b^{0,+}$AT/BAT1. In contrast, V142A and L223M, which were also found in normal subjects, did not affect or only slightly decreased the cystine transport activity compared with wild-type $b^{0,+}$AT/BAT1 (Figure 2). We also constructed V142A/L223M double mutant, which contains both V142A and L223M alterations because they are possibly located in the same allele. As shown in Figure 2, even the double mutation for V142A and L223M did not severely affect the functional activity.

Table 1 | Primers used for amplification of *SLC7A9* exons and their direct sequencing

	Sense primer	Antisense primer	Size of amplified fragment
Exon 2	5′-GAGCTTGCACTTGCGTCTTG-3′	5′-AATCAAAGAGTACATCTTCTGCCG-3′	299[a]
Exon 3	5′-TGGCCTTCTGGGCTGGGTC-3′	5′-AAGAGGGATACTGGCAGGGT-3′	307
Exon 4[b]	5′-AGCCTCCGGTGGGAGGAAG-3′	5′-GAGTCCCCAGACACCCTCTG-3′	388
Exon 5[b]	5′-AAAGGAGACTCTCTCCAGGG-3′	5′-ATGCTTCCTTGGAGATGGGCT-3′	292
Exon 6	5′-CCATCTTTCCCGTGGAGATACA-3′	5′-CAAACCCCAGAAAGGAGAACTC-3′	279
Exon 7	5′-CCACTAGCAGGGCCATTCAC-3′	5′-CGGGAAGGGCATCATGGAATAC-3′	316
Exon 8[b]	5′-CTGAACGTGGGTCTCCGTG-3′	5′-ACCTCCAGTGCTGACACCTG-3′	235
Exon 9	5′-CTCTTGGAGGCCGAGAAAGAC-3′	5′-GGGTGTTATTGCTTTCGCCGC-3′	214
Exon 10	5′-TGGTCTGCACTCTGGTCAGC-3′	5′-GGCATCTGGGTCATTTGGAAG-3	236
Exon 11	5′-CTTCTTCGGTCTTCTGTGAC-3′	5′-CTAGAAGGCATGCCCCTAGC-3′	314
Exon 12	5′-AGGGGGTACATGGAGTTCATAC-3′	5′-GTGACAGAGGTCTTGGAGTC-3′	366
Exon 13	5′-CAGGGTCTAGGTGACGCATC-3′	5′-TCAGCTGACTTGGCTACAAGAG-3′	218

[a]The size of the fragments amplified by PCR using sense and antisense primers described is indicated (bp).
[b]The primers for exons 4, 5, and 8 are identical to those for reference International Cystinuria Consortium.[12]

Table 2 | The mutagenic oligonucleotide primers[a]

SLC7A9 mutagenesis primers	
W69stop	5′-CCTGCCTCATCATAT(A)[b]GGCGGCTTGCGGGG-3′
G195R	5′-CATCATCATCATCAGC(A)GGCTGGTGCTCCTGGC-3′
V142A	5′-GTGCGCCCTTCTATG(C)GGGCTGCAAGCCTC-3′
L223M	5′-GGGAGCCATCAGC(A)TGGCGTTTTACAATGG-3′
N227D	5′-CCTGGCGTTTTAC(G)ATGGACTCTGGGCC-3′
R333Q	5′-CATTTACGTGGCGGGC(A)GGGAGGGTCACATG-3′
R333W	5′-CATTTACGTGGCGGGC(T)GGGAGGGTCACATG-3′
1105delA	5′-GGGTCACATGCTCAAA*GTGCTTTCTTAC-3′
P482L	5-GGAAGTGGTCCCAC(T)GGAGGAAGACCC-3
Alanine mutagenesis primers	
M477A	5′-GCACCTTCAGATGCTA(GC)GGAAGTGGTCCCAC-3′
E478A	5′-CTTCAGATGCTAATGG(CC)GTGGTCCCACCGGA-3′
V479A	5′-CAGATGCTAATGGAAG(CG)GTCCCACCGGAGGA-3′
V480A	5′-ATGCTAATGGAAGTGG(C)CCCACCGGAGGAAGA-3′
P481A	5′-GCTAATGGAAGTGGTC(G)CACCGGAGGAAGACC-3′
E483A	5′-GAAGTGGTCCCACCGG(CT)GAAGACCCTGAGTA-3′
E484A	5′-GTGGTCCCACCGGAGG(C)AGACCCTGAGTAACA-3′
D485A	5′-GTCCCACCGGAGGAAG(C)CCCTGAGTAACAAGC-3′
P486A	5′-CCCACCGGAGGAAGAC(G)CTGAGTAACAAGCTC-3′
E487A	5′-CCGGAGGAAGACCCTG(C)GTAACAAGCTCCGTC-3′,
Leucine mutagenesis primers	
M477L	5′-CTTCAGATGCTA(C)TGGAAGTGGTCCC-3′
E478L	5″-CGAATGCTAATG(CT)AGTGGTCCCACC-3′
V479L	5-GATGCTAATGGAA(C)TGGTCCCACCGGAG-3′
V480L	5′-CTAATGGAAGTG(C)TCCCACCGGAGGA-3′
P481L	5′-ATGGAAGTGGTC(C)TACCGGAGGAAGAC-3′
E483L	5′-GTGGTCCCACCG(CT)GGAAGACCCTGAG-3′
E484L	5′-GGTCCCACCGGAG(CT)AGACCCTGAGTAAC-3′
D485L	5′-CCACCGGAGGAA(CT)CCCTGAGTAACA-3′
P486L	5′-CCAGTAGGAAGACC(T)TGAGTAACAAGCTC-3′
E487L	5′-GGAGGAAGACCCT(CT)GTAACAAGCTCC-3′
P482X mutation primers	
P482G	5′-GGAAGTGGTGCCA(GG)GGAGGAAGACCCTG-3′
P482A	5′-GGAAGTGGTCCCA(G)CGGAGGAAGACCCTG-3′
P482S	5′-GGAAGTGGTCCCA(T)CGGAGGAAGACCCTG-3′
P482V	5′-GGAAGTGGTCCCA(GT)GGAGGAAGACCCTG-3′
P482I	5′-GGAAGTGGTCCCA(ATT)GAGGAAGACCCTG-3′
P482M	5′-GGAAGTGGTCCCA(AT)GGAGGAAGACCCTG-S[1]
P482F	5′-GGAAGTGGTCCCA(TTC)GAGGAAGACCCTG-3′
P482W	5′-GGAAGTGGTCCCA(TG)GGAGGAAGACCCTG-3′

[a]Sense strand primers are shown.
[b]Mutated nucleotides are shown in parentheses.
*One nucleotide has been deleted.

P482L mutation

Among 41 cystinuria patients examined, cystinuria-specific mutations of *SLC7A9* excluding apparently polymorphic changes (V142A and L223M) were found in 35 cases (Table 3). It is noted that 25 cases were P482L homozygotes and six cases were heterozygotes involving P482L mutations. Urinary excretion levels of cystine and basic amino acids in the P482L homozygotes, compound heterozygotes involving P482L mutations, and P482L obligate heterozygotes who exhibited no cystinuria symptoms are provided in Table 4. P482L homozygotes and compound heterozygotes exhibited a high level of urinary excretion of cystine, lysine, arginine, and ornithine, whereas P482L obligate heterozygotes exhibited a significantly lower level of excretion of these amino acids, which is still higher than the normal levels (Table 4).

We further examined two family pedigrees with P482L mutation (Figure 3). In Family 1, the proband 1-6 with a clinical history of nephrolithiasis was homozygous for P482L and showed a high level of excretion of cystine and dibasic amino acids (Table 5). The heterozygotes 1-2 and 1-3 showed a lower level of amino acid excretion (Table 5). The urinary amino acid excretion of 1-1 and 1-5 without P482L mutation was within the normal range. In Family 2, 2-3 and 2-5 were homozygous for P482L, which showed a high level of urinary amino acid excretion. Although 2-2 exhibited a relatively high urinary excretion level for a heterozygote, she did not have an episode of delivery or removal of cystine stones.

Protein characterization of $b^{0,+}$AT/BAT1 mutants

We performed Western blot analyses using an antibody raised against the C-terminus portion of human $b^{0,+}$AT/BAT1 on the crude membrane fractions prepared from COS-7 cells coexpressing wild-type or mutant $b^{0,+}$AT/BAT1 with rBAT. The antibody recognized a 41 kDa protein for wild-type $b^{0,+}$AT/BAT1 in the Western blot (Figure 4a). The band disappeared in the presence of antigen peptides in the absorption experiment, confirming the specificity of immunoreactions (data not shown). As shown in Figure 4a, the bands with the identical size were detected for G195R, N227D, R333W, and R333Q mutants. The anti-C-terminus antibody could not detect W69stop and 1105delA, which lack the C-terminus portions. Furthermore, the antibody could not detect P482L, which has a mutation in the C-terminus region for which the antibody was generated (Figure 4a).

We further performed Western blot analyses using an anti-myc antibody on the membrane fractions prepared from COS-7 cells coexpressing myc-tagged wild-type or mutated $b^{0,+}$AT/BAT1 with rBAT. The anti-myc antibody recognized the bands with identical size as those detected by the anti-$b^{0,+}$AT/BAT1 C-terminus antibody (Figure 4b). The rank order of the relative band intensity of myc fusion proteins for G195R, N227D, R333W, and R333Q mutants determined by the anti-myc antibody was identical to that of G195R, N227D, R333W, and R333Q detected by the anti-C-terminus antibody. The anti-myc antibody did not detect the protein products of W69stop ($\sim$7 kDa) and 1105delA ($\sim$38 kDa) with a myc epitope on their N-termini. In contrast to the anti-C-terminus antibody, the anti-myc antibody recognized the P482L with a myc epitope on its N-terminus (myc-P482L), indicating that myc-P482L is present almost in the same amount as that for wild-type $b^{0,+}$AT/BAT1 (Figure 4b).

Localization of wild-type and P482L proteins in polarized MDCK II cells

In order to determine the subcellular localization of P482L protein, we performed confocal fluorescence analysis on the MDCK II cells expressing GFP-$b^{0,+}$AT/BAT1 (GFP: green fluorescent protein) alone or both myc-rBAT and GFP-$b^{0,+}$AT/BAT1 or GFP-P482L. For the coexpression experiments, the cells positive for both GFP fluorescence and Alexa Fluor fluorescence (myc-rBAT positive) were used for the

Table 3 | Summary of $b^{0,+}$AT/BATI mutations in cystinuria patients

Mutation type	Status	Nucleotide change	Exon	Protein domain	Urinary cystine (nmol/mg Cr)	Number of patients
P482L	Homozygote	C1533T	13	C-terminus	2065.8±305.3[a]	25
P482L	Heterozygote	C1533T	13	C-terminus	ND	3
P482L	Compound heterozygote	G671A	5	TM5		
G195R		C1533T	13	C-terminus	2103.5	1
P482L	Compound heterozygote	C1085T	10	IL4		
R333W		C1533T	13	C-terminus	2628.4	1
P482L	Compound heterozygote	G1086A	10	IL4		
R333Q		C1533T	13	C-terminus	ND	1
R333Q	Homozygote	G1086A	10	IL4	ND	1
N227D	Heterozygote	A767G	6	TM6	ND	1
1105delA[b]	Homozygote	1105delA	10	IL4	2118.0	1
W69stop	Compound heterozygote	G294A		TM2		
1105delA[b]		1105delA	3	IL4	ND	1
V142A	Heterozygote[c]	T513C	4	EL2		
L223M		C755A	6	TM6	ND	4
Total						39

[a]Mean±s.e.m. (n=7).
[b]1105delA results in the frameshift after Val^{340}.
[c]It is not known whether V142A and L223M mutations of these patients are in the same alleles or not.
ND, urinary cystine level was not determined for these cases. Instead, urinary cystine excretion was confirmed by cyanide-nitroprusside test. Cystine stones were also confirmed by infrared spectrophotometry.

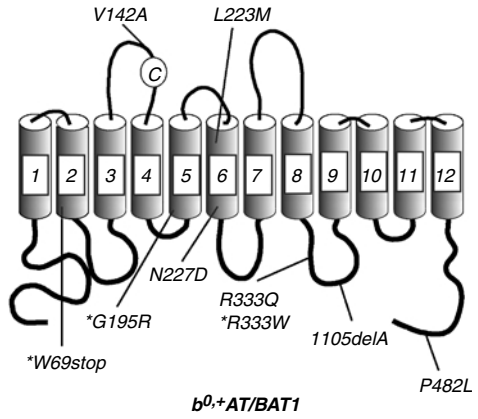

Figure 1 | Schematic representation of the mutations found in *SLC7A9* gene of patients with cystinuria. Nine mutations in *SLC7A9* gene found in 41 cystinuria patients are depicted at the corresponding amino acid residues in the 12-TM-domain model of $b^{0,+}$AT/BAT1 protein.[26] Seven mutations (W69stop, G195R, N227D, R333W, R333Q, 1105delA, and P482L) were cystinuria-specific, whereas two (V142A and L223M) were also found in the normal subjects (see text). W69stop, G195R, and N227D are located within the putative TM domains. R333Q, R333W, 1105delA, and P482L are located in the proposed intracellular loops or in the C-terminus intracellular domain. The mutations reported previously[12,16,18] were labeled with *.

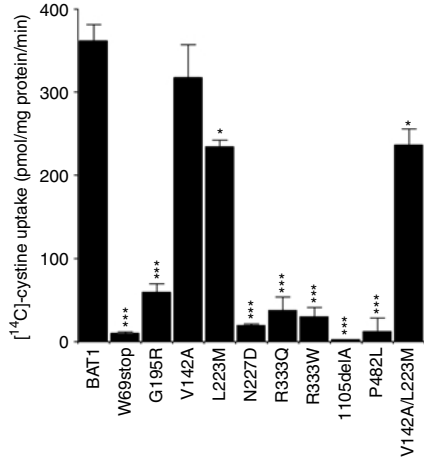

Figure 2 | Effects of *SLC7A9* mutations on the cystine transport activity. Wild-type $b^{0,+}$AT/BAT1 and indicated mutants were transiently expressed in COS-7 cells together with rBAT. The uptake of [^{14}C]L-cystine (100 μM) mediated by the expressed proteins was measured as described in 'Materials and Methods'. All transport values except those for V142A were significantly lower than those for wild-type coexpressed with rBAT. The transport values for L223M and V142A/L223M were higher than those for W69stop, G195R, N227D, R333Q, R333W, 1105delA, or P482L. V142A/L223M is a mutant that contains both V142A and L223M mutations. Asterisks indicate statistical significance (*$P<0.05$; ***$P<0.005$, Student's unpaired t-test).

analyses. As shown in Figure 5a, GFP-$b^{0,+}$AT/BAT1 protein was localized in the cytoplasm when expressed alone in MDCK II cells. Coexpression of GFP-$b^{0,+}$AT/BAT1 with myc-rBAT resulted in the apical localization of GFP-$b^{0,+}$AT/BAT1 protein in the MDCK II cells (Figure 5b). Similarly, GFP-P482L protein was also localized to the apical membrane when coexpressed with myc-rBAT (Figure 5c).

The plasma membrane expression of $b^{0,+}$AT/BAT1 and P482L proteins was further confirmed by surface biotinylation analysis (Figure 5d). HEK293 cells were used in this experiment for their higher efficiency in biotinylation analysis, probably due to the higher expression of the proteins. Consistent with the observation in COS-7 cells, myc-$b^{0,+}$AT/BAT1 but not myc-P482L showed

Table 4 | Urine amino acid levels in P482L homozygotes, compound heterozygotes, and obligate heterozygotes

		n	Cystine	Lysine	Arginine	Ornithine
P482L/P482L	Homozygotes	7	2065.8±305.3[a] (965.9–3056.6)[b]	8270.9±1185.3 (3866.8–11860.7)	3299.3±349.9 (1729.3–4482.8)	2233.0±383 (1032.1–4150.2)
R333W+P482L	Compound heterozygotes	1	2628.4	8855.4	3407.1	1592.7
G195R+P482L	Compound heterozygotes	1	2103.5	12911.5	6396.8	3744.5
P482L/+	Obligate heterozygotes	7	603.0±174.7[a, **] (56.3–1417.8)[b]	2534.7±623.5** (172.7–4781.8)	75.7±13.8** (25.6–118.4)	170.9±62.0** (18.2–354.5)
	Normal range		20–150	50–1300	10–60	5–40 (nmol/mg creatinine)

[a]Mean±s.e.m. (n=7).
[b]Range of amino acid excretion levels.
**$P<0.01$, versus homozygotes and compound heterozygotes (Mann–Whitney U-test).

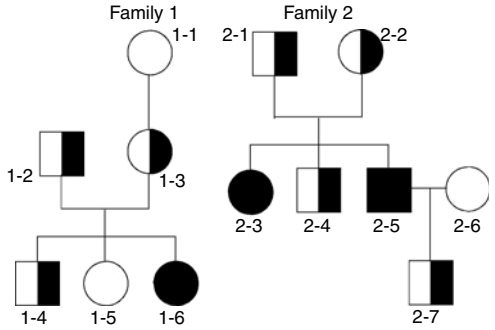

Figure 3 | Pedigrees of Japanese cystinuria families with P482L mutation. Two Japanese families (Families 1 and 2) with P482L mutation examined are shown.

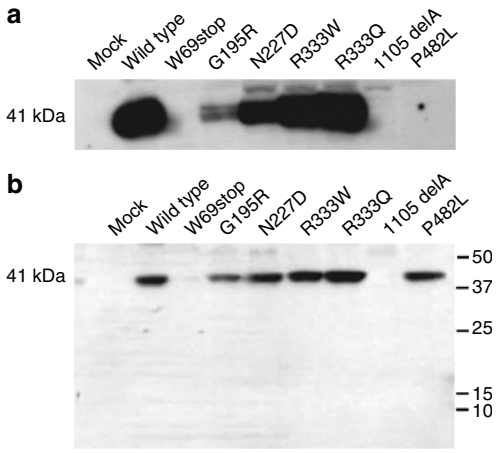

Figure 4 | Western blot analysis of $b^{0,+}$AT/BAT1 and its mutants. (**a**) $b^{0,+}$AT/BAT1 and its mutants were transiently expressed in COS-7 cells with rBAT. The Western blot analysis using an anti-$b^{0,+}$AT/BAT1 C-terminus antibody was performed on the membrane fraction prepared from the COS-7 cells. The anti-$b^{0,+}$AT/BAT1 C-terminus antibody recognized a 41 kDa band for wild-type $b^{0,+}$AT/BAT1 and its mutants except W69stop, 1105delA, and P482L. (**b**) An anti-myc antibody was used to detect $b^{0,+}$AT/BAT1 and its mutants to which a myc epitope was added at their N-termini. The myc-tagged proteins were transiently expressed in COS-7 cells with rBAT. In the Western blot, the anti-myc antibody recognized a 41 kDa band for wild-type $b^{0,+}$AT/BAT1 and its mutants including P482L.

Table 5 | Urinary excretion levels of cystine and dibasic amino acids of two family pedigrees

Individual no.[a]	Cystine	Lysine	Arginine	Ornithine	Sum
1-1	32.8	102.9	193.7	51.9	381.3
1-2	160.3	904.2	22.5	21	1108
1-3	791.1	3164.1	107.9	328.8	4391.9
1-4	385	2912.5	61.6	60.5	3419.6
1-5	64.7	222.8	23.1	20.1	330.7
1-6[b]	2240	7049	3538.3	2026.1	14853.4
2-1	255.6	1062.4	33.6	42.7	1394.3
2-2	1417.8	4012.9	100.3	354.5	5885.5
2-3	2932.6	9726.3	3440.7	2364.4	18464
2-4	ND	ND	ND	ND	ND
2-5[b]	1677.9	6370	2478.8	1692.7	12219.4
2-6	ND	ND	ND	ND	ND
2-7	891.7	4781.8	118.4	352.9	6144.8
Normal range	20–150	50–1300	10–60	5–40	(nmol/mg creatinine)

[a]The individual numbers are corresponded to those of members of the family pedigrees shown in Figure 4.
[b]1-6 and 2-5 are probands.
ND, Not determined.

[^{14}C]L-cystine uptake when coexpressed with rBAT in HEK293 cells (data not shown). As shown in Figure 5d, myc-$b^{0,+}$AT/BAT1 and myc-P482L proteins were detected at the plasma membrane when coexpressed with rBAT. The myc-$b^{0,+}$AT/BAT1 and myc-P482L proteins were not detected at plasma membrane when solely expressed (Figure 5d).

Effect of P482L mutation

In order to understand why P482L, a single amino acid alteration at the C-terminus of the transporter protein, resulted in the loss of transport function, we performed site-directed mutagenesis analyses. For the series of mutants in which residues between Met^{477} and Glu^{487} were systematically changed to alanine, no remarkable decrease was observed in the [^{14}C]L-cystine transport activity compared with wild-type $b^{0,+}$AT/BAT1 (Figure 6a). It is notable that the alteration of Pro^{482} to alanine did not affect the [^{14}C]L-cystine transport activity in contrast to the severe decrease in the transport activity observed for P482L. We, then, changed individual amino acid residues located between residues 477 and 487 to leucine (Figure 6b). We found that P481L, V479L, M477L, E478L, and V480L, in addition to P482L, exhibited a significant decease in the [^{14}C]L-cystine transport activity

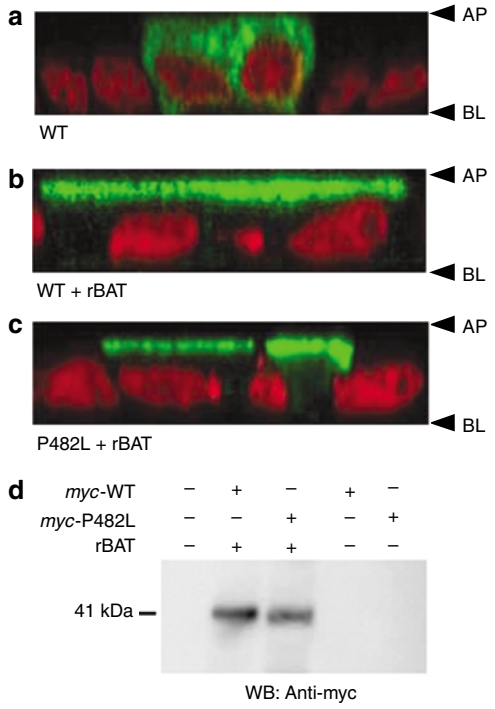

Figure 5 | Localization of P482L protein on the plasma membrane. Shown are the *x–z* images of confocal laser-scanning microscopic analyses on the MDCK II cells expressing (**a**) GFP-$b^{0,+}$AT/BAT1, (**b**) GFP-$b^{0,+}$AT/BAT1 with rBAT, and (**c**) GFP-P482L with rBAT. GFP-$b^{0,+}$AT/BAT1 and GFP-P482L fusion proteins were sorted to the apical membrane of the MDCK II cells when coexpressed with rBAT. In contrast, GFP-$b^{0,+}$AT/BAT1 fusion protein stayed in the cytoplasm when solely expressed. AP and BL indicate apical and basal sites of MDCK II cells, respectively. (**d**) Cell surface biotinylation analysis of $b^{0,+}$AT/BAT1 and P482L. HEK293 cells were transiently expressed with myc-$b^{0,+}$AT/BAT1 plus rBAT (lane 2), myc-P482L plus rBAT (lane 3), myc-$b^{0,+}$AT/BAT1 alone (lane 4), or myc-P482L alone (lane 5). Single bands of ~41 kDa were observed for myc-$b^{0,+}$AT/BAT1 and myc-P482L coexpressed with rBAT (lane 2 and 3). Green: GFP fluorescence; red: 4,6-diamidino-2-phenylindole fluorescence from nuclei.

compared with wild-type $b^{0,+}$AT/BAT1; however, the magnitude of the decrease was much less than that for P482L. In order to further investigate the effect of the alteration of Pro^{482} to Leu, we constructed mutants in which Pro^{482} is changed to various neutral amino acids with varied bulkiness in their side chains. As shown in Figure 6c, the alteration of Pro^{482} to amino acids with bulky side chains such as leucine, isoleucine, methionine, phenylalanine, and tryptophan severely decreased the [^{14}C]L-cystine transport activity, whereas the change to the amino acids with less-bulky side chains such as glycine, alanine, serine, and valine did not affect the functional activity.

DISCUSSION

In the present study, we examined cystinuria patients from oriental population (40 Japanese and one Korean) and found that mutations of *SLC7A9* gene responsible for the disease of the oriental population are quite different from those reported previously for European, North American, and

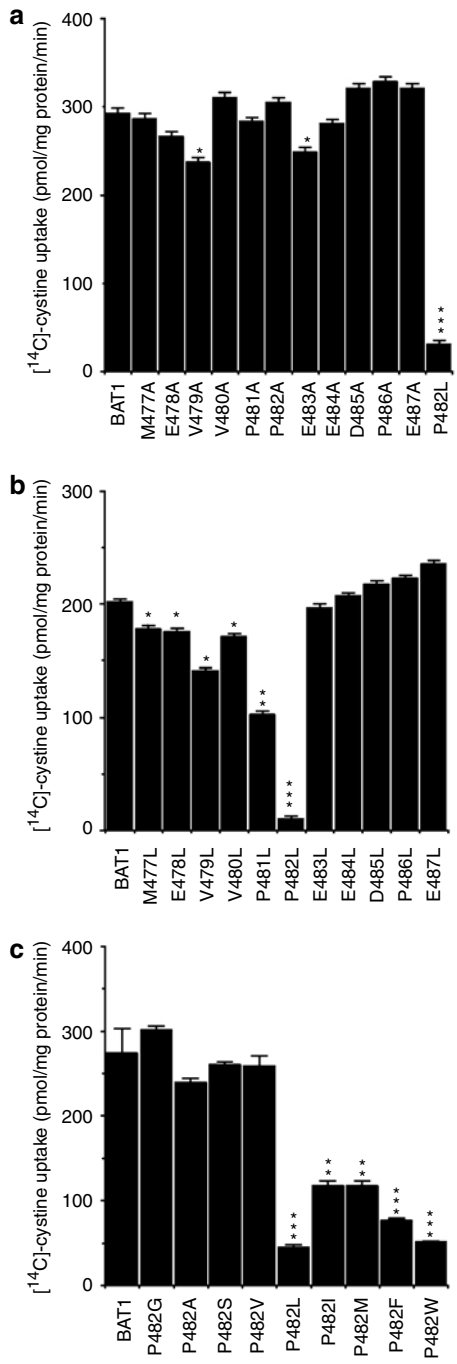

Figure 6 | Effects of site-directed mutagenesis of C-terminus of $b^{0,+}$AT/BAT1 on [^{14}C]L-cystine uptake. (**a**) The C-terminus amino acids between residues 477 and 487 of $b^{0,+}$AT/BAT1 were systematically mutated to alanine. The site-directed mutants exhibited no remarkable decrease in the uptake of [^{14}C]L-cystine compared with that of wild type except for P482L mutation. (**b**) The C-terminus amino acids between residues 477 and 487 of $b^{0,+}$AT/BAT1 were systematically mutated to leucine. When Pro^{482} was changed to leucine, the mutants expressed with rBAT exhibited remarkable decrease in the uptake of [^{14}C]L-cystine (100 μM). (**c**) Pro^{482} of $b^{0,+}$AT/BAT1 was mutated to amino acids with varied bulkiness in their side chains. The alteration of Pro^{482} to leucine, isoleucine, methionine, phenylalanine, and tryptophan remarkably decreased the transport activity, whereas the alteration to glycine, alanine, serine, and valine did not change the transport activity. Asterisks indicate statistical significance (*$P<0.05$; **$P<0.01$; ***$P<0.005$, Student's unpaired *t*-test).

Libyan Jewish.[12,16,18] In contrast to W69Stop, G195R, and R333W reported previously,[12,16,18] N227D, R333Q, 1105delA, and P482L found in the present study are novel cystinuria-specific mutations, suggesting that these mutations are unique to Japanese or Asian. It is noted that 31 out of 35 cases with cystinuria-specific mutations examined in the present study involved P482L mutation, whereas this mutation has not been reported for European, North American, and Libyan Jewish population.[12,16,18] It is, therefore, supposed that P482L mutation is prevailing in Japanese and possibly in the other Asian population. G105R, the most frequent mutation for European, North American, and Libyan Jewish population ($\sim$25% of non-type I cystinuria cases),[18] was not found in the present study. It is interesting that two cystinuria-specific missense mutations R333Q and R333W found in the present study affect the same amino acid residue, in which R333Q was only found for Japanese cases. Arg^{333} is located in the putative intracellular loop between TM domains 8 and 9 and conserved for human members of heterodimeric amino acid transporter family.[18] It is, thus, proposed that this amino acid residue is critical in the transport function or in the structural framework for the light chains of heterodimeric amino acid transporters.

For P482L mutation most abundantly found in the present study, we examined two family pedigrees and confirmed Mendelian inheritance and phenotype–genotype correlation (Figure 3 and Table 5). The homozygotes of this mutation exhibited severe cystinuria phenotype with episodes of excretion or removal of renal stones and high level of urinary excretion of cystine and dibasic amino acids. Compared with normal individuals, P482L heterozygotes exhibited a higher level of excretion of cystine and dibasic amino acids into urine, consistent with the characteristics of non-type I cystinuria (Table 5). Relatively large range of variation in the amount of urinary excretion was observed among heterozygotes (2-1, 2-2, and 2-7). This might be due to the possible genetic alterations of $b^{0,+}$AT/BAT1 or rBAT that could not be detected in the present study, variations in other factors related to the transporter systems, or differences in diet and metabolism. We found three P482L heterozygotes who suffer from nephrolithiasis. For these patients, no mutation was found in the exons of *SLC3A1* gene encoding rBAT. Although we cannot exclude the involvement of additional mutations of *cis*-regulatory elements of *SLC7A9* gene and *SLC3A1* gene or the mutations of unidentified genes that might be essential for cystine transport, P482L heterozygous mutation could possibly cause cystinuria symptoms dependent on the condition of the patients, which has been reported for classic type II cystinuria with severe phenotypes.[16,20]

P482L is the missense mutation affecting the C-terminus of $b^{0,+}$AT/BAT1. As shown in Figure 2, this mutation results in the loss of function of $b^{0,+}$AT/BAT1 protein coexpressed with rBAT in COS-7 cells, indicating that Pro^{482} plays pivotal role in the functional expression of the transporter. Loss of function of P482L mutant is supposed not due to the loss of protein expression or lack of ability to be sorted to the apical membrane based on the following reasons: first, the anti-myc antibody recognized the band for myc-tagged P482L with the intensity similar to that of wild-type $b^{0,+}$AT/BAT1 (Figure 4b); second, the GFP-tagged P482L protein was sorted to the apical membrane when coexpressed with rBAT in MDCK II cells similar to GFP-tagged wild-type $b^{0,+}$AT/BAT1 (Figure 5b and c); finally, surface biotinylation study revealed that P482L protein as well as wild-type $b^{0,+}$AT/BAT1 protein was detected at the plasma membrane upon coexpression with rBAT in HEK293 cells (Figure 5d). In Figure 4b, the protein products of W69stop and del1105A were not detected. This might be due to the rapid degradation of the immature proteins. A recent study on the crystal structure of *Escherichia coli* 12-membrane-spanning transporters indicated that the substrate binding sites are located in the hydrophilic pocket surrounded by TM helices, suggesting that their N- and C-terminal intracellular domains are not directly involved in the substrate binding and translocation of substrates.[21,22] Mammalian 12-membrane-spanning transporters phylogenetically related to the bacterial 12-membrane-spanning transporters are supposed to possess the analogous structure and operate based on the similar structural trait.[23] In order to examine the roles of Pro^{482} in the C-terminus intracellular domain of $b^{0,+}$AT/BAT1, we performed site-directed mutagenesis analyses. In the first series of experiments, C-terminus amino-acid residues between Met^{477} and Glu^{487} were systematically changed to alanine. Surprisingly, no remarkable decrease was observed in the cystine transport activity even when Pro^{482} was changed to alanine in spite of the severe decrease in the function for Pro^{482}-to-Leu alteration. This indicates that Pro^{482} itself is not essential for the function of $b^{0,+}$AT/BAT1 protein but the incorporation of leucine residue at position 482 interferes with the functional expression.

We, thus, generated additional site-directed mutants in which Pro^{482} was changed to various neutral amino acids. As shown in Figure 6, the alteration of Pro^{482} to amino acids with bulky side chains affected the function of $b^{0,+}$AT/BAT1, whereas the changes to residues with less bulky side chains did not reduce the functional activity. It is, thus, suggested that the bulky side chains incorporated at the C-terminus of $b^{0,+}$AT/BAT1 interfered with the functional expression of $b^{0,+}$AT/BAT1. By examining the site-directed mutants in which residues between Met^{477} and Glu^{487} were systematically changed to leucine, it was found that leucine alteration affected the function of $b^{0,+}$AT/BAT1 only when quite restricted residues were changed to leucine. Based on these observations, we, thus, propose that the bulky side chain incorporated at the position 482 of $b^{0,+}$AT/BAT1 somehow suppressed the transport function possibly by interfering with intra- or intermolecular interactions. The further investigation would lead to the understanding of the novel regulatory mechanisms of heterodimeric amino acid transporters as well as the role of P482L mutation in the pathogenesis of cystinuria.

In the present study, we have identified several novel mutations of *SLC7A9* from oriental population and found that mutations are quite different from those reported previously for European, North American, and Libyan Jewish. Our results contribute toward understanding the distribution and frequencies of cystinuria-related mutations of *SLC7A9*.

MATERIALS AND METHODS

Subjects

Forty-one cystinuria patients (40 Japanese and one Korean) from 39 independent families were studied. All had an episode of delivery or removal of cystine stones. Urinary excretion of cystine and dibasic amino acids was determined in 24 h urine samples by quantitative ion-exchange chromatography or reverse-phase high-performance liquid chromatography. The amino acid content was corrected per gram of creatinine. In all patients whose urinary cystine excretion was analyzed quantitatively, cystine excretion was over 800 nmol/mg creatinine. Urinary hyperexcretion of dibasic amino acids was also confirmed. The urinary excretion of other neutral amino acids was within normal ranges for all patients. For the patients whose urinary amino acid levels were not quantitatively analyzed, the urinary cystine excretion was confirmed by cyanide-nitroprusside test and their cystine stones were analyzed by infrared spectrophotometry.[3] Genomic DNA was obtained from the patients and the members of the selected family pedigrees. Genomic DNA was also obtained from 50 unrelated normal individuals who served as controls. The study protocol was approved by the Institutional Research Boards of Chiba University Graduate School of Medicine and of Kyorin University School of Medicine. All study subjects gave written informed consent, and the ethics committee of Chiba University Graduate School of Medicine and of Kyorin University School of Medicine gave permission for the analyses in relation to cystinuria.

Determination of *exon–intron* boundaries of *SLC7A9*

The location and sequence of all exon–intron boundaries were determined by direct sequencing of the products obtained by PCR amplification of genomic DNA with randomly designed cDNA-derived oligonucleotide primers, using an ABI PRISM Sequencer (Perkin Elmer, Wellesley, MA, USA). *SLC7A9* consisted of 13 exons. The codon for the translation-initiator methionine (ATG) was located in exon 2, whereas the termination codon TAA was located in exon 13. The exon–intron boundaries we determined have turned out to be identical to those obtained by deducing the recently released genomic DNA sequence of *SLC7A9* (accession no. AC008805).[18]

Mutation analysis and direct sequencing

Genomic DNA was extracted from whole blood using the Wizard Genomic DNA Purification Kit (Promega, Madison, WI, USA). Twelve pairs of oligonucleotide primers (Table 1) were synthesized in order to amplify all exons of *SLC7A9* gene by PCR for direct sequencing. In all cases, sequencing of both strands of the PCR products was performed.[24] Mutation analysis of *SLC3A1* gene was performed for the above-described 41 cystinuria patients using oligonucleotide primers as described elsewhere.[25]

Construction of mutant cDNAs

All cDNA mutants were constructed by using the QuikChange site-directed mutagenesis kit (Stratagene, La Jolla, CA, USA) according to the manufacturer's instructions. The mutagenic oligonucleotide primers are shown in Table 2. Proper construction of the mutated cDNAs was confirmed by complete sequencing.

Functional expression in COS-7 cells

cDNAs for human rBAT and those for wild-type or mutated human $b^{0,+}$AT/BAT1 in pcDNA3.1(+) were expressed transiently in COS-7 cells using LipofectAMINE™2000 (Invitrogen, Carlsbad, CA, USA) following the manufacturer's instructions.[26] For co-transfection, 10 μg of cDNA for $b^{0,+}$AT/BAT1 or its mutants and 10 μg of rBAT cDNA were diluted into 1 ml of opti-MEM reduced-serum medium (Invitrogen, Carlsbad, CA, USA) and mixed with 60 μl LF2000 reagent diluted in 1 ml opti-MEM reduced-serum medium. After incubation for 20 min at room temperature, the mixture was applied to COS-7 cells maintained in a tissue culture dish (90 mm diameter) with 70–90% confluence. At 24 h after transfection, the transfected cells were collected and seeded on a 24-well plate (2×10^5 cells/well) in fresh medium. Amino acid uptake measurements were performed at 48 h after transfection of the plasmids as described elsewhere.[26]

Anti-human $b^{0,+}$AT/BAT1 antibodies

Oligopeptides (QMLMEVVPPEEDPEC) corresponding to amino acid residues 474–487 of human $b^{0,+}$AT/BAT1 were synthesized. Anti-peptide antibody was produced as described elsewhere.[27,28]

Construction of the fusion proteins

The fusion proteins in which myc and GFP epitopes were fused to the N-terminus of wild-type and mutant $b^{0,+}$AT/BAT1 were generated. The coding regions of cDNAs for the wild-type and mutant $b^{0,+}$AT/BAT1 were amplified by PCR using primers containing restriction enzyme cleavage sites for *Hin*dIII, *Xho*I, *Eco*RI, or *Kpn*I. After digestion with *Hin*dIII and *Xho*I or *Eco*RI and *Kpn*I, the fragments were ligated with pCMV-Taq3 vector (Stratagene, La Jolla, CA, USA) digested with *Hin*dIII and *Xho*I or pEGFP C2 vector (Clontech, Mountain View, CA, USA) digested with *Eco*RI and *Kpn*I, respectively. Proper construction was confirmed by DNA sequencing.

Western blotting

COS-7 cells were co-transfected with cDNAs for human rBAT and those for wild-type, mutated human $b^{0,+}$AT/BAT1 or their myc-tagged products as described above. At 48 h after transfection, the transfected cells were collected and homogenized as described elsewhere.[29] The anti-human $b^{0,+}$AT/BAT1 (1:2000) antibody or anti-myc (1:2000) antibody (Invitrogen, Carlsbad, CA, USA) was used as the primary antibody. To verify the specificity of immunoreactions by absorption experiments, the membranes were treated with primary antibodies in the presence of antigen peptides (50 μg/ml).[29]

Confocal laser-scanning microscopy

MDCK II cells provided by Dr Dietrich Keppler (European Molecular Biology Laboratory, Heidelberg, Germany) were cultured as described.[30] For localization of $b^{0,+}$AT/BAT1 and P482L mutant protein, MDCK II cells were grown on transwell membranes (membrane diameter 24 mm, pore size 3.0 μm; Costar, Corning, NY, USA) for 1 week (100% confluence) and then co-transfected with cDNAs for myc-tagged human rBAT (1 μg) and those for GFP-tagged wild-type human $b^{0,+}$AT/BAT1 or GFP-P482L (1 μg) using LipofectAMINE™2000. Cells were fixed with 4% paraformaldehyde in phosphate-buffered saline and permeabilized with 0.5% Triton X-100 in phosphate-buffered saline containing 5% goat serum.

Membranes were incubated with an anti-myc (1:500) antibody (Invitrogen, Carlsbad, CA, USA) at room temperature for 1 h. After three washes with phosphate-buffered saline, the membranes were incubated with Alexa Fluor 546 goat anti-mouse IgG (Molecular Probes, Eugene, OR, USA) as a secondary antibody for 1 h. Argon and HeNe laser beams were used for excitation at 488 nm for GFP and 543 nm for Alexa Fluor 546 visualization, respectively. Nuclei were stained with 4,6-diamidino-2-phenylindole nucleic acid staining for 10 min and visualized by excitation at 405 nm with Diode 405 laser. Images were acquired using Carl Zeiss LSM510 META laser-scanning confocal microscope (Carl Zeiss, Frankfurt, Germany).

Cell surface biotinylation

Surface biotinylation of $b^{0,+}$AT/BAT1 and P482L mutant at the plasma membrane of HEK293 cells was performed as describe elsewhere.[31,32] myc-tagged $b^{0,+}$AT/BAT1 and myc-P482L were detected with an anti-myc (1:2000) antibody (Invitrogen) and horseradish peroxidase-conjugated anti-mouse IgG as a secondary antibody (Jackson ImmunoResearch, West Grove, PA, USA).

Statistical analysis

Data are expressed as mean $\pm$ s.e.m. Statistical differences were determined using Student's unpaired *t*-test. Mann–Whitney *U*-test was used to analyze urinary amino-acid levels among different genotypes. Differences were considered significant at the level of $P<0.05$.

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